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Long-term trends in radial growth of Siberian spruce and Scots pine in Komi Republic (northwestern Russia)

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Komi is situated on the eastern boundary of the European part of Russia, in the boreal region where large areas of natural forest still exist. Using radial growth measurements it was possible to attain positive long-term trends of growth in Scots pine (*Pinus sylvestris*) and Siberian spruce (*Picea obovata*) in the Komi Republic. Increases in the radial growth of Siberian spruce in the forest–tundra were 134% and in the northern taiga zone 35% over successive 50-year periods from 1901 to 1950 and from 1951 to 2000. Respectively, in the middle taiga zone a 76% increase in radial growth was found (over 100 years), whilst in the southern taiga zone the changes were not statistically significant. The increase in radial growth of Scots pine in the northern taiga zone was 32%. In the middle taiga zone the radial growth increase in Scots pine was 55% and in the southern taiga zone the changes were not statistically significant. The long-term growth trends of Komi were compared with those in other parts of Europe.

Introduction

According to the World Meteorological Organization (WMO 2004) the Earth's global surface temperature has increased since measurements were first recorded in 1861. During the 20th century the increase was more than 0.6 °C. The rate of change since 1975 is roughly three times that for the previous 100 years. Analyses of proxy data for the northern hemisphere indicate that this increase in temperature during the latter part of the 20th century is unprecedented when compared to the last millennium (WMO 2004).

There is clear evidence during recent decades that the climate in the Komi Republic in northwestern Russia has changed (Lopatin *et al*. 2006, 2007). Analysis of climate data for the Komi Republic (Lopatin 2007) showed that during the past 30 years the temperature increased by 0.43 °C for the entire region. Mean annual precipitation during the past 30 years decreased by 2.2%. However the changes in climate have varied in different vegetation complexes. Although all vegetation zones showed an increase in mean annual air temperature (Lopatin 2007), the mean annual precipitation increased only in the middle taiga and the southern taiga. In other vegetation complexes a decreasing trend was identified (Lopatin 2007). Borehole temperature measurements in the Komi Republic also indicate a strong subsurface warming, reflecting changes in the trends of both surface air temperature and precipitation (Oberman & Mazhitova 2004).

Understanding how growth trends in northwestern Russia's unmanaged forests responded to global changes in the past and how they will respond in the future is very important for the development of the European forest sector as a whole. Additionally, forestry and forest industries are the backbone of the economies of the regions making up northwestern Russia. Furthermore, the ratification of the Kyoto Protocol by Russia in October 2004 created a renewed impetus to reduce the uncertainty of the role of Russian forests in carbon exchange with the atmosphere, to create transparent methods for monitoring terrestrial carbon sinks and fluxes, and to provide information for the decision-making process concerning management of carbon in forest ecosystems as a part of the overall national forest management strategy (Strakhov *et al*. 2003). A major impediment to understanding terrestrial carbon exchange is the lack of field measurements.

A case study in the Komi Republic (Drobyshev *et al*. 2004) showed that the latewood width of Scots pine (*Pinus sylvestris*) correlates positively with the temperature in April–May and July–August of the current growth season and with the July–August precipitation of the previous year, while earlywood width was positively affected by precipitation in May and November of the previous year. This is in accordance with the observation that the growth of conifers in the boreal zone positively correlates with growing season temperatures (Briffa *et al*. 1988). Physiologically, this results from the fact that in the boreal zone, the carbon gain of the trees is typically limited by temperature during the growing period. As long as water is not a limiting factor for the radial growth, increased carbon gain in the tree ring should positively correlate with increment.

On the European scale an attempt to identify forest growth trends was conducted in 1993–1996 (Spiecker *et al*. 1996, Spiecker 1999b). Results of this project represent only 17% of the forest area of northwestern Russia. The main purpose of the project was to analyze whether site productivity has changed in European forests during the last decades. It was possible to observe an increasing growth trend in most cases, although, in some studies (Nöjd 1996, Mielikäinen and Sennov 1996) a decreasing trend was reported at specific sites. However, these previous studies of growth trends were conducted only in secondary even aged forests in Europe (Spiecker *et al*. 1996).

The aim of this paper is to identify long-term trends (> 30 years) in radial growth of Siberian spruce (*Picea obovata*) and Scots pine (*Pinus sylvestris*) from untouched forest ecosystems of the Komi Republic. The hypothesis here is that forest site productivity has changed in the Komi Republic during the last decades due to the trends in climate.

Material and methods

Study area, selection of sites and trees

Komi is one of the easternmost boreal regions of European Russia where large areas of natural forest still exist (Lopatin *et al*. 2006, 2007, 2007b). The annual average air temperature varies between +1 °C in the southern part of the Republic and –6 °C in the northern part, with the growing season (days with daily average air temperature above +10 °C) being between 10 and 45 days. Annual rainfall decreases from 700 mm in the south to 450 mm in the north. The accumulation of thick snow cover (70–80 cm) is a characteristic of the winter period which lasts for 130–200 days (Stolpovski 1997).

In the Komi Republic there is no available prior data on forest growth because of the lack of permanent research plots within the observation period. Because forest growth cannot be analyzed in a direct way, reconstructed radial increment of dominant trees is used in this study as an indirect measure of changes in the development of site productivity in the past (Spiecker 1999a).

The material was collected along a transect from the south of Komi (southern taiga of boreal forests) to the Arctic spruce timberline (Fig. 1; Lopatin 2007). The study stands were assigned

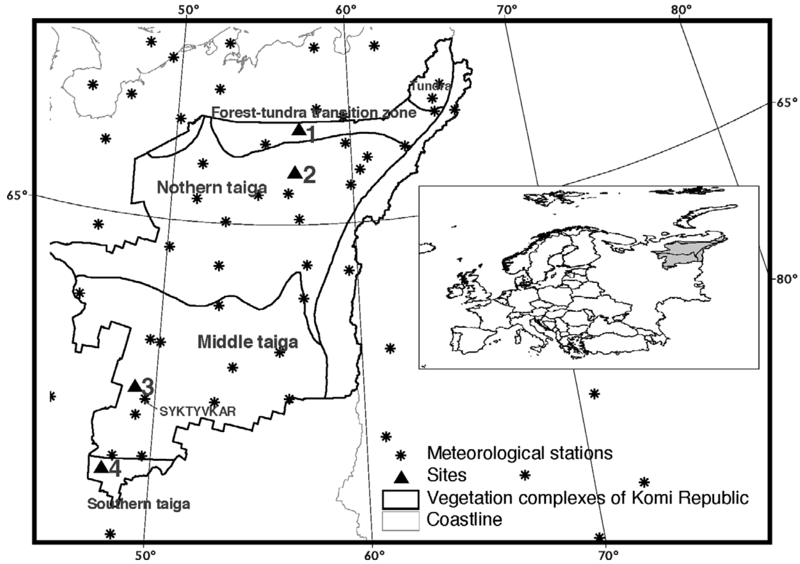

Fig. 1. Sampled stands and sub-zones of taiga boreal forests. Borders of vegetation complexes according to Kozubov and Degteva (1999) (site numbers as in Table 1).

to 'sub-zones' according to their geographical position in the taiga sub-zones of boreal forests (Table 1). The selection of sites and trees, sample preparation and measurements are described in Lopatin *et al*. (2006, 2007, 2007b).

The sites were selected using GIS datasets of forest management units, old forest inventory maps and satellite images TERRA ASTER (scene size 60 × 60 km) with a spatial resolution of 15 m. In the procedure for site selection the main aim was to find representative site types and at the same time exclude possible forest management or any other past human impact. Sites with a low productivity index (class 5, according to the classification system for Russian forest productivity) represent 70% of the forest area of Komi Republic (Kozubov and Taskaev 1999). Therefore, the results from different geographical areas were comparable. Differences in site characteristics, such as exposure, soil properties, topography or vegetation development, are assumed to have been averaged out accordingly. To obtain the information about changes in site productivity trees of different ages from comparable sites were selected. The stands were selected according to the following criteria for site conditions:

- spruce or pine dominating species (proportion of species composition was close to equal);
- low site index (class 5, according to the Russian forest productivity classification system);
- multistoried mature stands represented by trees of 3–5 different age classes.

In most parts of Komi, forest stands are represented by trees of several age classes (Havimo *et al*. 2007). Therefore, sample trees were chosen from trees not dominated by older trees. The sample trees were expected to reveal homogeneity in their tree-ring pattern; they showed no obvious signs of near-neighbor competition or forest management. Mature dominant trees were chosen from different diameter classes, healthy looking with straight, unbroken stems and regularly shaped crown. A large crown ratio and the occurrence of relatively thick dead branches or large knots in the lower part of the bole have been used as indicators of the dominant crown class status of the tree in the past (Kahle *et al*. 2008). The selected trees represented similar site conditions but different tree ages. The sample trees in the stands were expected to have a common growth trend, which was influenced by a large portion of climatic effects and other factors which differ among individuals and from site to site. At each site an averaging process, during the building of the mean radial growth curve, helped to minimize the influence of other factors.

Prior to felling, for visual assessment of the tree ring pattern, the core of the tree was

Table 1. Tree ring data collected in Komi Republic in 2003–2005.

Site	Zone	Location coordinates	Siberian spruce			Scots pine		
			Number of trees	Time span	Min–max (mean) age	Number of trees	Time span	Min–max (mean) age
1	Forest–tundra transition zone*	66°41´260´´N 56°49´142´´E	16	1812–2005	71–192 (115.6)	–	–	
2	Northern taiga	65°59´697´´N 57°48´820´´E	16	1878–2005	37–126 (75.3)	20	1924–2005	52–80 (69.3)
3	Middle taiga	61°44´834´´N 50°34´910´´E	40	1779–2005	38–225 (104.3)	45	1786–2005	34–218 (93.6)
4	South taiga	60°33´615´´N 49°26´945´´E	30	1917–2005	18–89 (52.8)	22	1877–2005	28–127 (73)
Total			102			87		

* The Scots pine trees not found in forest-tundra transition zone.

extracted with an increment borer. This allowed exclusion of trees affected by competition in the past. Discs from the stem were cut at 1- or 2-meter (or a few centimeters higher or lower if a branch or something else made ring measurement difficult) intervals using a chain saw. North direction was marked on the disks.

To determine changes in tree radial growth the concept of cohort comparison was also applied: differences in average radial growth curves between trees with different germination dates were used as indicators for changes in forest site productivity over time. The radial growth series were divided into age classes so that only data derived from rings within a specific age range were averaged. This gives tree-growth estimates within which the age of trees is held roughly constant over time (Briffa *et al*. 1992). The target ages of the trees to be selected were 50 years for the young (1951–2000) and 90 years for the older (1901–1950) trees and age limits should be between a minimum of 30 and maximum of 130 years. These age limits were set in order to exclude juvenile and senescent developmental stages during which trees might be less responsive to environmental stimuli (Kahle *et al*. 2008).

The discs and cores were dried in normal room conditions and then polished. The prepared surfaces were measured using the WinDENDRO system (Guay *et al*. 1992), and using a traditional microscope based system in case of extremely narrow rings.

The measurements of the tree rings were carried out on a minimum of two radii per disk, though usually on four radii. Where the samples were cored, the two cores per tree were measured to decrease the variation within the tree, and to exclude peculiarities caused by non-climatic factors.

The identification of long-term forest growth trends

The definition of growth trends in this study is similar to that in previous research projects (Spiecker *et al*. 1996). A growth trend can be defined as a persistent change in the average rate of growth. Growth trends within this project are indicated by long-term (more than 30 years) site-related deviations of observed *versus* expected growth.

There are two methodological approaches chosen for the identification of long-term growth trends using the measurement of tree rings from the sampled trees:

- chronology building,
- comparison of radial increment in similar cambial age.

Building chronologies and evaluating long-term forest growth trends using those chronologies is one of the most widely used methods of identifying forest growth trends (Mielikäinen and Sennov 1996, Sinkevich and Lindholm 1996, Spiecker *et al.* 1996, Spiecker 1999b, Grudd *et al.* 2002).

In order to maximize the climatic signals in tree ring series, other factors should be minimized. For example, a typical sample might display exponentially declining growth with age, the classic biological growth curve. Standardizing the sample using a spline curve results in data values that represent a departure from the "expected" value for a given year. The above-mentioned procedure usually is an attempt to remove the growth trends due to normal physiological ageing processes and changes in the surrounding forest community. Therefore individual ring-width series were indexed using spline curves with a 50%-frequency response of 60 years (Cook and Kairiukstis 1990). This approach was selected due to the high amount of variance in the dataset because of using the trees from different age cohorts for chronology building. The deviation from mean value over the whole period of observation was calculated and then smoothed by employing a 10-year running average. The ARSTAN program was used to undertake this detrending process (Holmes *et al.* 1986, Grissino-Mayer *et al.* 1997, Holmes 1999). Time periods for the analysis were selected based on chronology confidence statistic of Expressed Population Signal (EPS) (Wigley *et al.* 1984). EPS was computed as a function of mean inter-tree correlation and sample size.

The interpretation of trends in tree-ring series is neither easy nor unequivocal. The main problem with their interpretation is the method of standardization (Innes 1991). In this study we also used raw radial increment series, in an attempt to avoid any bias introduced by standardization. Radial growth was analyzed within age classes to check whether there were any size differences between the radial increment of trees of the same cambial age in different periods (Briffa *et al.* 1992, Becker *et al.* 1994, Lebourgeois and Becker 1996, Lebourgeois *et al.* 2000). Data were averaged year by year, separately, for the two species. Two age classes were considered: 1–50, 51–100, confidence limits for each curve were estimated at $p = 0.05$ based on the number of sampled trees using Microsoft Excel. The radial increment series were summarized for the two equal periods to estimate changes in long-term cumulative increment. The statistical significance of the differences between the curves was tested by comparing the confidence limits of means estimated at $p = 0.05$ based on the number of measured tree rings. Only the series derived from disks and cores where the innermost rings allowed the estimation of pith location and cambial age were included in the analysis (Table 1).

Results

The south taiga zone

Standardized tree-ring chronologies of Siberian spruce show an increasing growth trend for the period 1920–1960 (Fig. 2A) and then negative and positive trends for the period 1960–2005.

The cambial age approach (Fig. 3A) shows higher radial increment of younger generation (at first 30 cambial years) than older generation of Siberian spruce. The confidence intervals between the two groups overlap. Therefore one could make a conclusion, that using collected samples there are no statistically significant long-term changes in radial increment of Siberian spruce in the southern taiga.

The standardized tree-ring chronologies of Scots pine (Fig. 4A) show an increase in growth from 1900 to 1940, then decrease from 1940 to 1970 and thereafter an increase. Cambial age approach show higher radial increments of trees germinated 50 years ago than those germinated

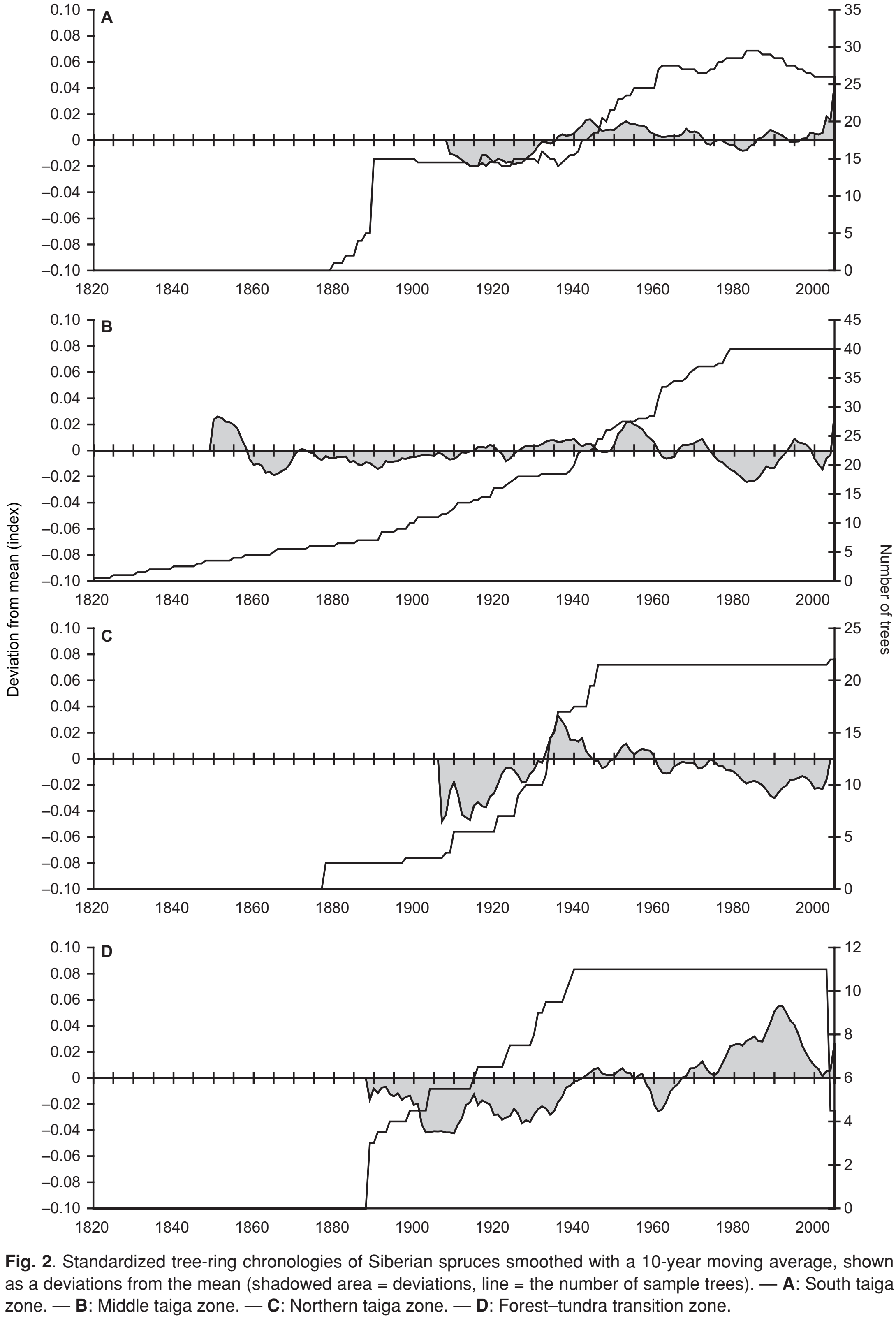

Fig. 2. Standardized tree-ring chronologies of Siberian spruces smoothed with a 10-year moving average, shown as a deviations from the mean (shadowed area = deviations, line = the number of sample trees). — **A**: South taiga zone. — **B**: Middle taiga zone. — **C**: Northern taiga zone. — **D**: Forest–tundra transition zone.

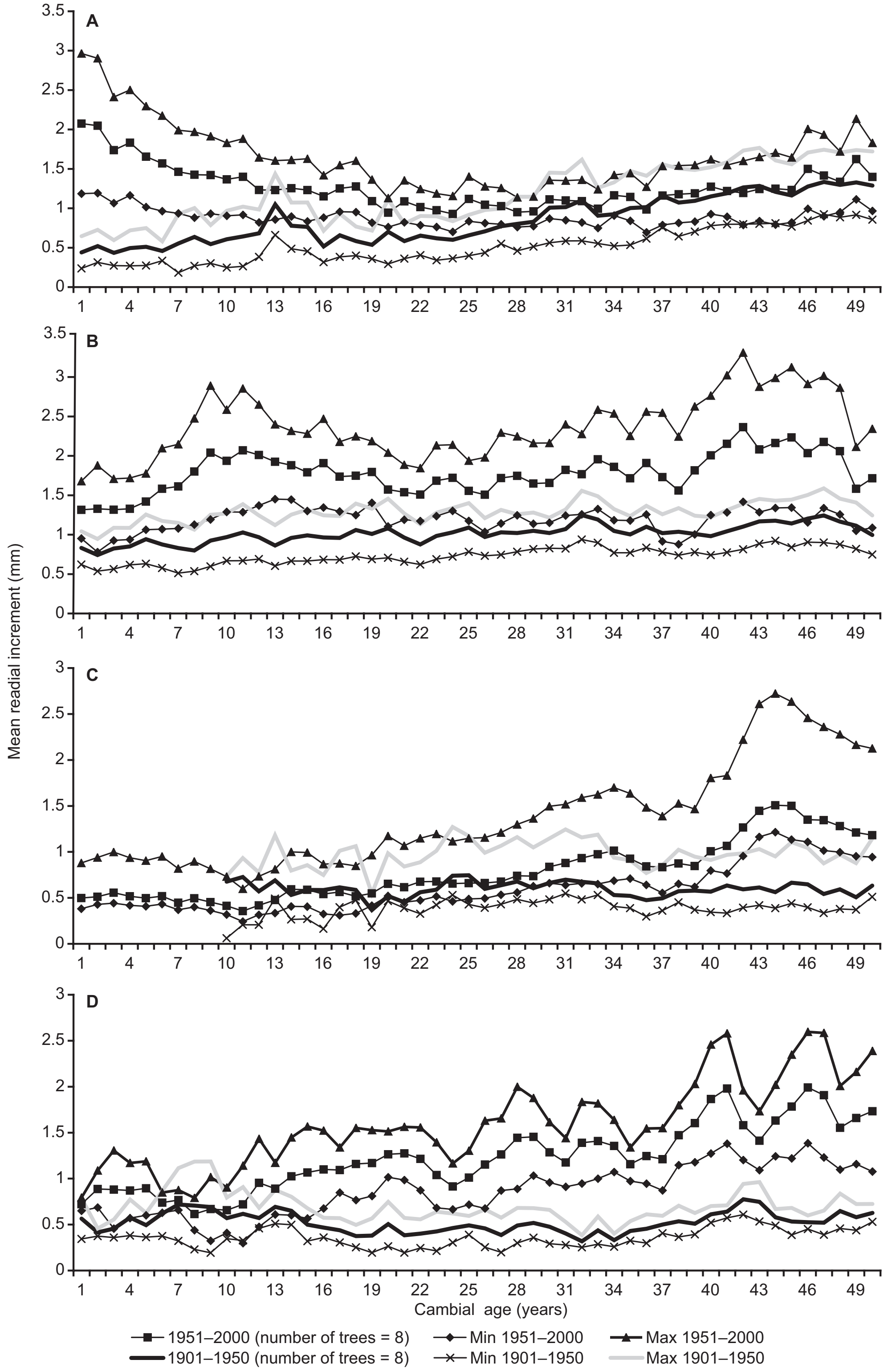

Fig. 3. Mean radial increment of Siberian spruces of different age *versus* similar cambial age. — **A**: South taiga zone. — **B**: Middle taiga zone. — **C**: Northern taiga zone. — **D**: Forest–tundra transition zone.

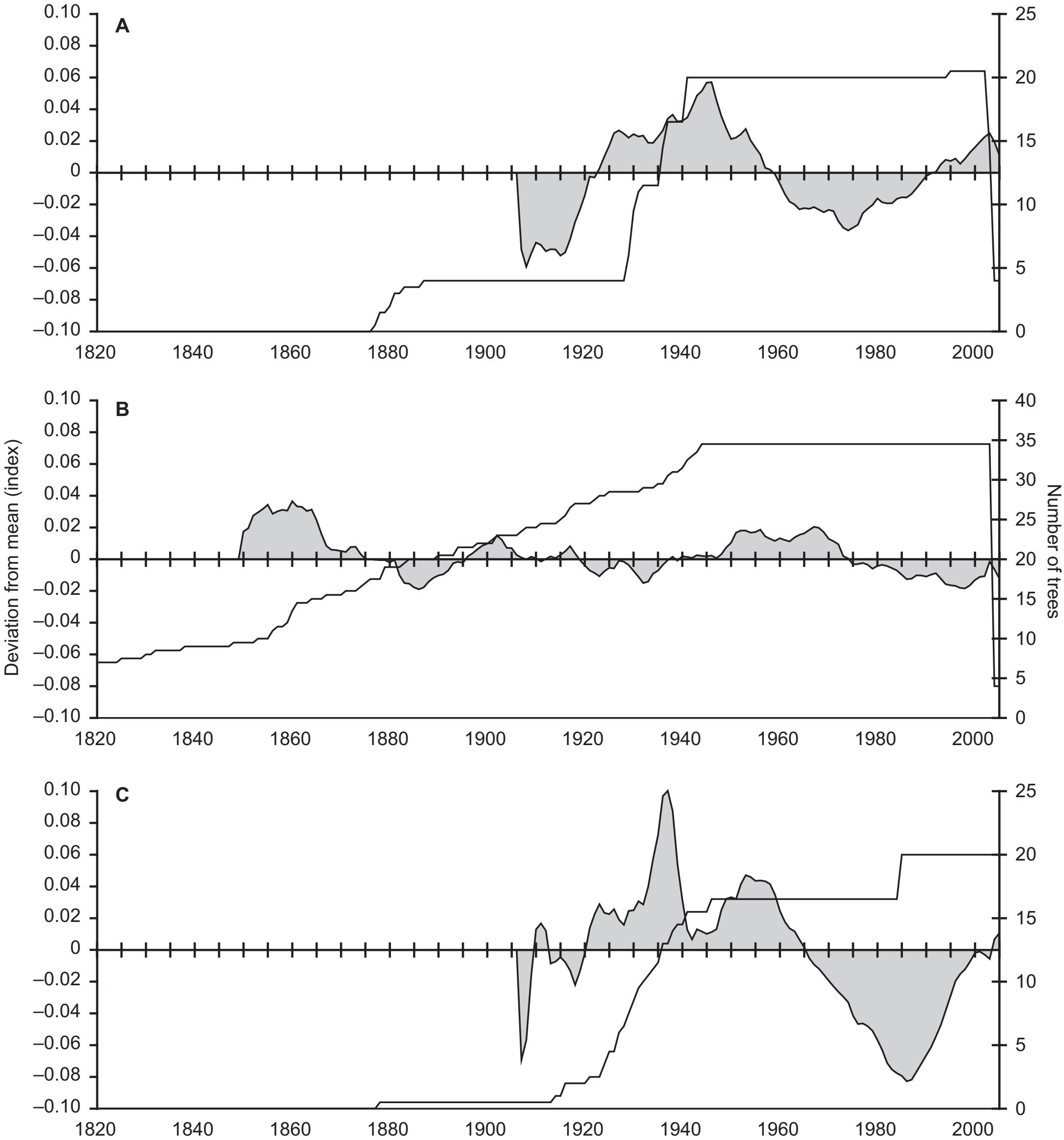

Fig. 4. Standardized tree-ring chronologies of Scots pine smoothed with a 10-year moving average, shown as a deviations from the mean (shadowed area = deviations, line = the number of sample trees). — **A**: South taiga zone. — **B**: Middle taiga zone. — **C**: Northern taiga zone.

100 years ago, but this increase is not statistically significant (Fig. 5A).

The middle taiga zone

The standardized tree-ring chronologies of Siberian spruce (Fig. 2B) show an increasing trend from 1900 till 1960. The non-standardised mean radial increment chronologies from different cambial age (Fig. 3B) show a statistically significant increase in radial increment. Siberian spruces in the middle taiga sub zone are growing faster now than they grew 50 years ago.

The radial increment of Scots pine has varied during the last 100 years with periods of high (1930–1970) and low (1900–1930) growth (Fig. 4B). The non-standardized mean radial incre-

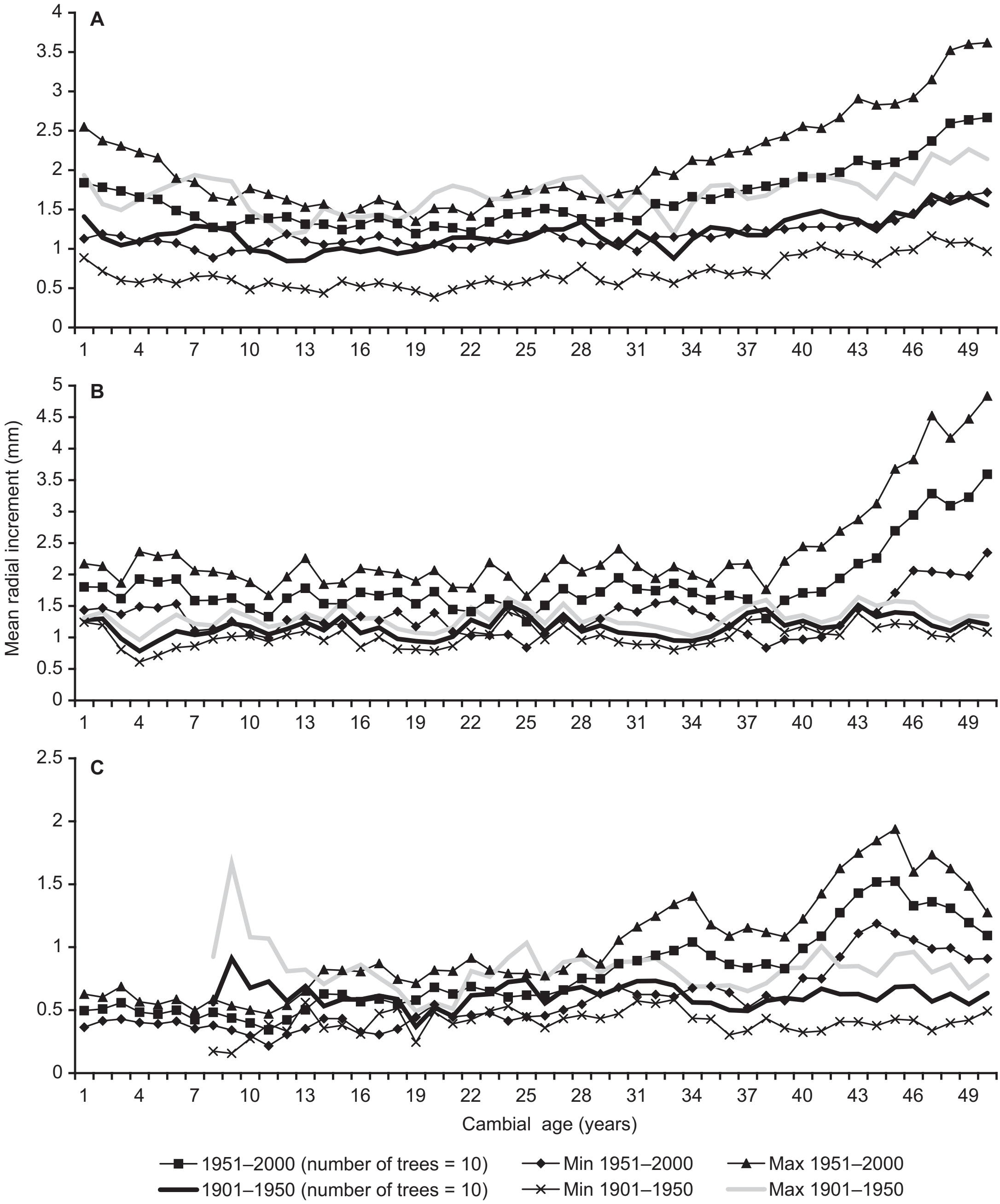

Fig. 5. Mean radial increment of Scots pine of different age *versus* similar cambial age. — **A**: South taiga zone. — **B**: Middle taiga zone. — **C**: Northern taiga zone.

ment chronologies from different cambial age (Fig. 5B) show the increase in radial increment. Using collected samples this increase is not statistically significant over the analyzed period. There are several periods where confidence intervals of two age groups are overlapping.

Northern taiga zone

Standardized tree-ring chronologies of Siberian spruce in the northern taiga zone (Fig. 2C) show a decrease in growth since 1943. However the cambial age approach (Fig. 3 C) shows no statistically significant difference in radial increment. The younger generation is growing faster after 30 cambial years, but this increase is significant only after 40 cambial years.

The radial increment of Scots pine has varied periodically during the past 80 years (Fig. 4C). There is an increasing trend before 1950. We found an increasing trend since 1969 that is confirmed by the cambial age approach (Fig. 5C). It is notable that in the northern taiga zone the younger generations of both Siberian spruce and Scots pine are growing faster after 30 cambial years, but this increase is significant only after 40 cambial years.

In the northern taiga zone there was an increase in the growth of conifers during the past 20 years, though the response of Scots pine to changing conditions is more marked than the response of Siberian spruce.

Forest–tundra transition zone

The smoothed standardized tree-ring chronologies of Siberian spruce (Fig. 2D) show a strong trend of increasing radial increment from 1940 that is close to a linear increase (R^2 = 0.91). During the period 1890 to 2003 there has never been as high a mean radial increment as seen in the last 30 years of the study period. This increase is confirmed by the cambial age approach using data comprised of raw tree ring measurements (Fig. 3D). Siberian spruce trees in the forest–tundra transition zone are growing faster now than they grew 50 years ago. In the forest–tundra transition zone there is a positive long-term growth trend in the growth of Siberian spruce.

There were no pines found in the northern forest–tundra transition zone.

Comparison of growth trends in different forest zones

The long-term growth trends of Siberian spruce and Scots pine were studied in four subzones of the taiga boreal forests in the Komi Republic (Table 2). The approach implemented in our study estimates the sum of mean raw ring widths in trees of similar cambial age for two equal growth periods from two age classes. Table 2 summarizes the findings and shows the increments for the two different periods: 1901–1950 and 1951–2000. This evaluation of all subzones showed a positive trend. This result is statistically significant because the confidence intervals of the mean annual increments were not overlapping for both species in all sub zones of taiga (Figs. 6 and 7).

Discussion

As there was no comparable forest statistical data (based on consistent forest area and species composition) available with annual resolution for the last 100 years and it is impossible to use forest inventory data for identifying long-term forest growth trends, the dendrochronological approach was chosen to identify long-term forest growth trends (variation of radial growth on time span more that 30 years) in the Komi Republic

Table 2. Long-term growth trends of Siberian spruce and Scots pine in the Komi Republic using the method of calculating the sums of radial increment for the equal intervals.

Zone	Siberian spruce			Scots pine		
	Increment sum (mm) 1901–1950	Increment sum (mm) 1951–2000	Increase (%)	Increment sum (mm) 1901–1950	Increment sum (mm) 1951–2000	Increase (%)
Forest–tundra transition	26.20	61.29	133.91	–	–	–
Northern taiga	29.21	39.36	34.77	29.81	39.34	31.97
Middle taiga	50.58	89.11	76.18	59.82	92.62	54.83
Southern taiga	42.42	65.02	53.27	59.83	81.84	36.80

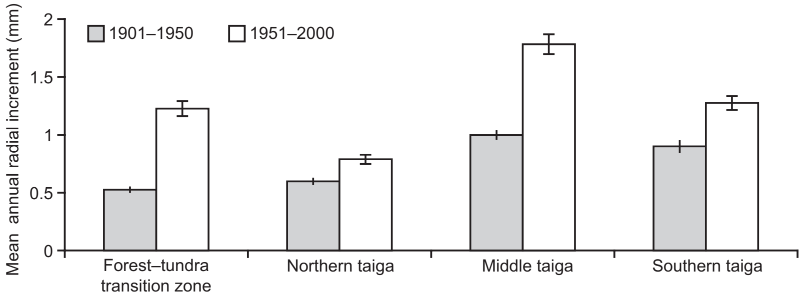

Fig. 6. Mean annual radial increment of Siberian spruce for the equal time intervals

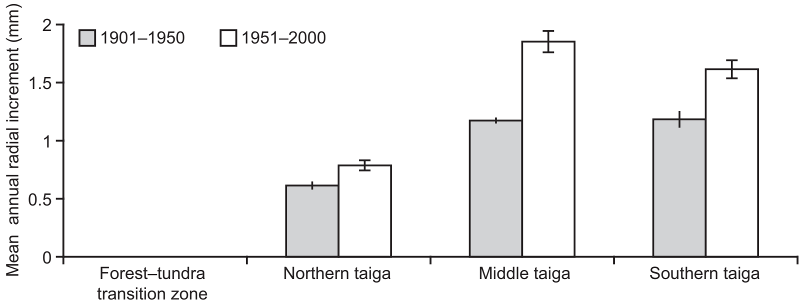

Fig. 7. Mean annual radial increment of Scots pine for the equal time intervals.

Using radial growth measurements in similar cambial age it was possible to attain positive long-term trends of growth in Scots pine and Siberian spruce in the Komi Republic. The most significant results were achieved by comparison of radial increment in similar cambial age. Statistically significant changes in mean annual radial increment were identified for both species in four forest zones (Figs. 6 and 7). However, the most pronounced changes were found in radial growth of Siberian spruce in middle taiga (Fig. 3B) and forest–tundra transition zone (Fig. 3D). The changes in other cases were statistically significant, but less pronounced due to the possible insufficient number of samples or magnitude of changes.

Combination of time series analysis with mean annual changes showed increases in the radial growth of Siberian spruce in the forest–tundra were 134% and 35% in the northern taiga. Respectively in the middle taiga zone a 76% increase in radial growth was found, whilst in the southern taiga zone the changes were not statistically significant. The increase in radial growth of Scots pine in the northern taiga zone was 32%. In the middle taiga zone the radial growth increase in Scots pine was 55% and in the southern taiga zone the changes were not statistically significant.

The climate data shows a general increase in the annual air temperatures and decrease in the annual precipitation in the Komi Republic. The highest increase in growth of Siberian spruce was observed in the forest–tundra transition zone. This finding allows us to conclude that environmental conditions for those species, on the limits of their distribution, are now better than before. In the northern, middle and southern subzones of taiga the response of Siberian spruce to changing conditions is more obvious than that of Scots pine (Table 2).

There could be various causes for the general increase in growth of both Scots pine and Siberian spruce in the Komi Republic but the driving factor is temperature. Comparison of changes in increment sums (Table 2) with trends in temperature and precipitation (Lopatin 2007) showed that the highest increase in radial increment is in the forest–tundra zone where the temperature increased and annual amount of precipitation decreased. The temperature increase in the middle taiga zone is higher than in northern taiga. A similar difference was found in changes in sums of radial increment. It was confirmed by Drobyshev (2004) that the growth of conifers in the Komi Republic is more related to the temperature than to precipitation. Similar results were found in Finland at the same latitude (Mäkinen *et*

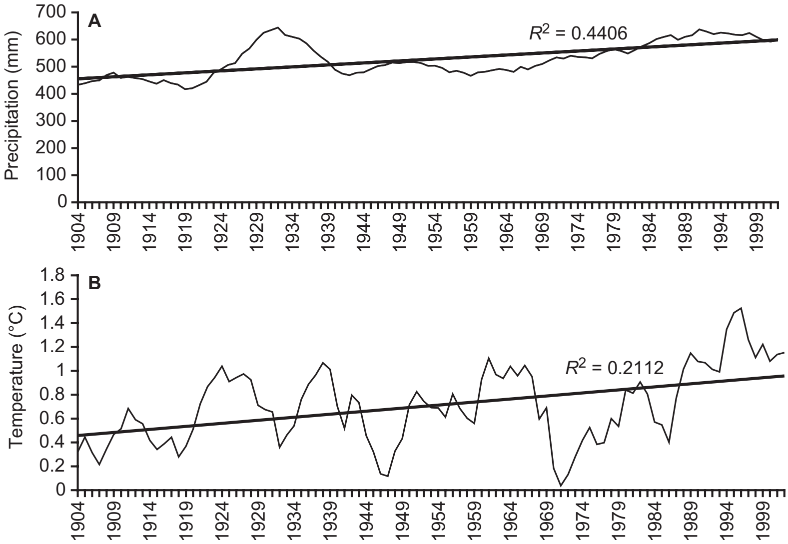

Fig. 8. (**A**) Annual precipitation and (**B**) 10-year running mean annual temperature at the meteostation Syktyvkar (61°40´N, 50°51´E).

al. 2001). Another cause of the increased forest growth is an increase in the amount of nitrogen available for plants (Spiecker 1999b). However, the factors driving the site productivity increase in the Komi Republic are still uncertain. The trends of increasing temperature and amount of precipitation are not equal in the Komi Republic (Lopatin 2007). However, the trend of precipitation increase is closer to a linear increase (R^2 = 0.44), than the temperature increase (R^2 = 0.22) (Fig. 8). In Komi, the annual evaporation is less than the annual precipitation (Table 3) explaining why the temperature conditions in Komi are limiting factors for the functioning of forest ecosystems. This fact could also explain the absence of a clear gradient from south to north in growth increase from the southern taiga to the northern taiga. It could be a spatial and temporal shift as the trees respond to local climate change.

Forest growth trends in Europe (Spiecker *et al*. 1996) combined with the results of our studies are shown in Fig. 9. Comparisons of trends in the Komi Republic with trends at the same latitude (i.e. Finland, Sweden, and Norway) show that there are different forest growth trends from this study. The explanation for this difference could be the different climate conditions or differences in regional tropospheric responses to long-term solar activity variations (Raspopov *et al*. 2007).

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Table 3. Climate characteristics in different taiga sub zones in the Komi Republic (Galenko 1983).

Zone	Vegetation period* (days)	Precipitation (mm)		Annual evaporation (mm)
		May–October	October–April	
Northern forest–tundra transition	117	235	190	125
Northern taiga	143	290	190	175
Middle taiga	158	330	260	200–250
South taiga	177	370	250	300

*Days with daily average temperature above +5 °C.

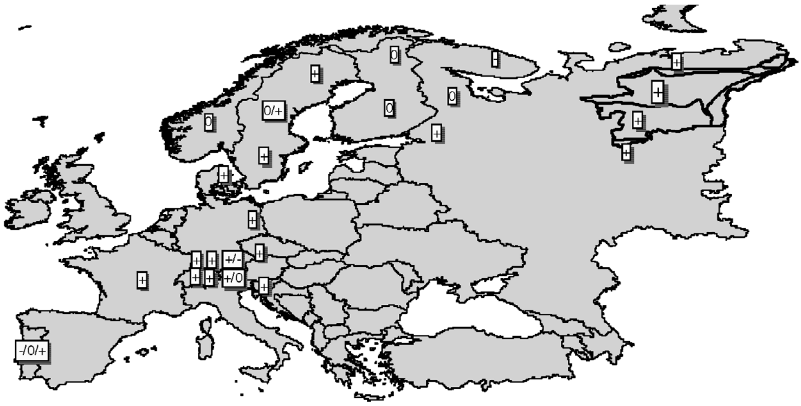

Fig. 9. Map showing the long-term forest growth trends in Europe according to Spiecker *et al.* (1996) and this study in Komi Republic. "Trend": + = positive, – = negative, 0 = no trend.

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